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Magnetic resonance ultrashort echo time spin-echo imaging of the deepest layers of articular cartilage

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Magnetic resonance imaging (MRI) has emerged as an invasive radiologic technique to assess and characterize cartilage lesions in the setting of injury and degenerative joint disease. However, most of the currently available clinical and research MRI techniques, including proton-density weighted fast spin echo (FSE) [1], T2-weighted FSE [2], T2 mapping [3], and steady state free precession imaging [4] have focused on the superficial layers of cartilage. There is a growing interest in the deepest layers of articular cartilage, including the calcified and deep radial layers located just superficial to the subchondral bone [5,6]. There has been an emphasis on the role of lesions in the deep radial and calcified layers of cartilage in the pathogenesis of osteoarthritis [6,7]. The lack of imaging evaluation of the deep layers of cartilage stems largely from the fact that it is technically difficult to image.

Conventional MRI pulse sequences with echo times (TE) of 1 ms or greater provide little or no detectable signal from many tissues and tissue components that have very short T2 relaxation times, such as calcified cartilage, menisci, tendons, ligaments and some forms of soft tissue calcification [8]. By using half-sinc radiofrequency (RF) pulses, radial mapping of *k*-space, rapid transmit/receive switching, and variable rate selective excitation, nominal TEs as short as 8 μs have been achieved with ultrashort TE (UTE) imaging [9,10]. Therefore, the UTE pulse sequences make it possible to directly image tissues with very short T2 and their adjacent tissues [11]. Although short T2 tissues are detectable with UTE sequences, positive visualization of deep layers of cartilage is limited by the presence of high signals from long T2 water and fat.

The dual-echo gradient-echo UTE acquisition has been used previously to suppress long T2 signals in knee cartilage two-dimensional (2D) imaging [8]. With this approach, the second echo is subtracted from the first one, which is equivalent to band pass filtering. This selectively suppresses the signal from the longer T2 components, and typically provides high contrast in the short T2 range. However, the 2D UTE free induction decay (FID) acquisition is sensitive to eddy currents, gradient anisotropy and timing errors [12]. The latter echoes in this acquisition are sensitive to off-resonance effects. Therefore, we developed a dual-echo spin echo UTE acquisition approach. This letter describes the development and implementation of dual-echo spin-echo UTE sequences, and testing its relative efficacy in terms of signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) in imaging deep radial and calcified layers of articular cartilage.

1 Materials and methods

As shown in Figure 1, the multi-echo spin-echo UTE acquisition technique was developed where a spin-echo image

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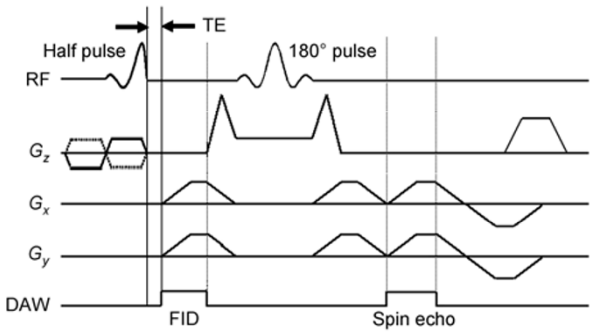

Figure 1 Pulse sequence diagram for 2D dual-echo spin-echo UTE imaging.

was generated by introducing a refocusing 180° RF pulse following UTE FID acquisition. Spin-echo data acquisition starts after the refocusing gradient so that the same *k*-space trajectory can be used for both FID and spin-echo on-line image reconstruction.

The performance of the proposed 2D dual-echo spin-echo UTE sequence was illustrated by experiments on a 3T GE Signa TwinSpeed scanner (GE Healthcare Technologies, Milwaukee, Wisconsin, USA). A quadrature knee coil was used for volunteer knee cartilage imaging. The imaging plane was chosen to be perpendicular to the deep layers of cartilage to minimize partial volume effects. A field of view (FOV) of 8–16 cm was employed with a slice thickness of 1.7–2.5 mm. Multiple interleaved slices were acquired using a TR of 200–600 ms, a flip angle of 60°, 511 half projections, a 62.5 kHz bandwidth, and a 50%–200% slice gap. During reconstruction, the *k*-space data were first regridded onto a 512×512 Cartesian grid using a Kaiser-Bessel kernel, followed by an inverse two-dimensional fast Fourier transformation to generate UTE images. For quantitative assessment of the quality of spin-echo and gradient-echo UTE images, both SNR and CNR measurements were performed. CNR between the deep layers of cartilage and superficial layers of cartilage and fat were calculated as their signal difference over background noise.

2 Results

Preliminary results show that UTE spin-echo acquisition provides significantly better image contrast between deep and superficial layers of cartilage (CNR=8.7) than UTE gradient echo acquisition (CNR=4.9). Conventional UTE FID acquisition provides the highest mean SNR of 56.5 for deep layers of cartilage. Echo subtraction significantly increased the image contrast between the deep layers and superficial layers of cartilage from 6.1 to 11.8. However, contrast between deep layers of cartilage and fat is still low.

The 180° RF pulse in a spin-echo UTE sequence refocuses the long T2 water and fat spins, and is therefore less sensitive to off-resonance effects. The subtraction image from UTE spin-echo acquisition significantly improved CNR over that from dual-echo gradient-echo acquisition. However, this technique requires a larger slice gap because a broader 180° RF pulse is required to more accurately refocus the broad slice profile that resulted from a half pulse excitation. A large flip angle close to 90° and a longer TR is also helpful.

3 Discussion

Subtraction of the spin-echo image from the first FID image may result in better suppression of long T2 water and fat signals, thus improving the delineation of the deep layers of cartilage. Compared with the spin-echo UTE sequence, gradient-echo UTE sequence is sensitive to eddy currents, field homogeneity and gradient non-linearity. Half pulse excitation requires the summation of two acquisitions with the slice selection gradient polarity reversed, so that a conventional slice profile is formed. Gradient profile distortion may result in improper weighting of the excitation and mismatch between the two acquisitions with non-ideal cancellation of the imaginary parts of the complex signals and out-of-slice signal contamination. Corrections of the residual slice-select gradients and time-varying main field $B_0(t)$ caused by eddy currents are helpful in reducing out-of-slice signal contamination.

The disadvantage of multiple-echo spin-echo UTE sequences used in this study is that it is a 2D acquisition with a slice thickness of 1.7–2.5 mm and a gap of 50%–200% slice thickness. Partial volume effects may significantly degrade the depiction of lesions, which may improve using three-dimensional UTE acquisition [13].

In conclusion, the 2D UTE sequence combined with multiple-echo spin-echo acquisition, with later-echo subtraction, can depict either the superficial layers or the deep layers of knee cartilage on a conventional clinical scanner with a degree of delineation previously not possible. UTE imaging with these modifications show substantial potential of being a powerful radiologic modality for the imaging of cartilage injury and osteoarthritic diseases.

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